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A GROUNDBASED INFRARED SKY SURVEY

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University of Arizona, Tucson, Arizona 85721

Contract No. F 19628 70-C-0046
Project No. 5130

ANNUAL TECHNICAL REPORT
30 September 1970

Contract Monitor: Stephan D. Price
Optical Physics Laboratory

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ABSTRACT

A Groundbased Infrared Sky Survey

The design, construction, operation and performance of a survey of th sky at infrared wavelengths is reported. A preliminary survey at 5 microns was conducted. This was followed by the more elaborate system using 8 detectors at 11 microns. Information concerning absolute calibration and performance is given.

ANNUAL TECHNICAL REPORT
CONTRACT NO. AF 19628-70-C-0046

I. Introduction:

In this report, we will summarize the results obtained during the first year of our groundbased infrared sky survey. As indicated in the Statement of Work and in the List of Milestones, the ultimate objective of this program is to survey the celestial sphere in a systematic fashion at infrared wavelengths accessible from the ground. In addition to the survey program, we have utilized our multiband (1.5 to 25 micron) photometric equipment to determine the characteristics of as many bright infrared sources as possible under the given limitations of manpower, budget and telescope time. This work has also been closely correlated with our efforts to make celestial observations in the wavelength interval beyond 25 microns which is not accessible from the ground. Through the combined efforts of these two programs, we are now able to accurately describe the radiative properties of a large number of infrared sources over the wavelength interval extending from 1 to 1000 microns. In this report, a brief summary of these results will be presented. However, most of this material is in some stage of publication in the scientific literature, and a complete bibliography is included. We will also review the observational results of the survey which has, so far, been limited to 5 and 10 microns. This report includes a section in which the technical experience gained in the design, construction and operation of a groundbased infrared survey system is discussed in detail. In particular, we are now able to give definitive results on the limiting performance of apparatus of this type. This body of information should be useful in comparing groundbased surveys to surveys conducted from high altitude or orbital platforms, and it constitutes one of the major results obtained under this contract. Finally, an accurate assessment will be made of the project status at the end of September, 1970.

II. The 5 Micron Survey:

Because of the low background level in the 5 micron atmospheric window and because many infrared stars are known to peak near 5 microns, we initiated a preliminary survey effort at this wavelength in the fall of 1969, immediately after the start of the contract. A single detector was used on the 28-inch telescope with an instantaneous field of view of 5 x 5 arcminutes. 700 square degrees were surveyed at a flux limit of about 5×10^{-15} watts/cm^2/micron. No unidentified sources were detected unambiguously; however, on November 22, 1969, the signature of a very bright source, 15×10^{-15} w/cm^2/μ, was detected at $20^h\ 10.^m2$; $+38^\circ\ 41'$ (1950). Repeated efforts to confirm this source some weeks later were not successful.

III. The 10 Micron Survey:

In Section V we discuss the technical aspects of the survey in detail; here we give the observational results as they stand at the end of September, 1970. A number of different filter-bolometer-modulator combinations were used in an effort to optimize the various parameters; thus, these results are not perfectly homogeneous with respect to wavelength, flux limit or field of view. However, all or part of the 7.5 to 13.5 micron atmospheric window was used.

The 10 micron survey observations started April 10, 1970. From that date, until the start of the rainy season in late June, 23 observing days produced usable data. Also included in the final total sky area covered are two nights of selected surveying in September, 1970, which were concentrated near positions of suspected sources.

The total sky covered was 463 square degrees. The following tabulation indicates what proportion of the sky was covered for three flux levels

Flux 1.5×10^{-14} w/cm^2/μ -- 463 sq. degrees

7×10^{-15} w/cm^2/μ -- 208 sq. degrees

3×10^{-15} w/cm^2/μ -- 121.7 sq. degrees

The first includes both night and day observations. The second includes all usable night observations, both noisy and better nights, and all selected survey areas. The third includes only good nights, which also includes most of the areas observed in the selected surveys.

From these observations, three low probability sources were found and are listed below:

1)	April 25	$5^h\ 34^m.3 \pm .1$	$-6^\circ\ 1^m \pm 1^m$ (1950)	s/n = 1:1
2)	April 26	$9^h\ 12^m.3 \pm .2$	$+40^\circ\ 20^m \pm 4^m$ (1970)	s/n = 1:1
3)	May 9	$21^h\ 11^m.7$	$+40^\circ\ 38^m \pm 1^m$ (1970)	s/n = 2:1

The third object was considered to have the greater probability of existence, but subsequent search did not redetect it. The first object had an interesting coincidence with an object observed in rocket flights, reported by Walker and Price (ref. 1) but a later search did not confirm it. The second object also has not been confirmed.

IV. Infrared Radiative Properties of Celestial Sources:

In our first six month technical report, we gave 5, 10 and 22 micron

magnitudes or fluxes at one or more of these wavelengths for 175 objects, including 89 bright stars, 58 "infrared stars", 4 "infrared nebulae", 12 "infrared galaxies" and 12 planetary bodies. These magnitudes and fluxes were determined by comparison of unknown objects to certain "standard stars" whose magnitudes and absolute fluxes are accurately determined. Table 1 lists the M(5μ), N(10.2μ) and Q(22μ) magnitudes and flux densities for the primary standard stars now in use at Arizona. The absolute flux calibration is based on Saiedy's (1960) (ref. 2) absolute calibration of the solar flux (ref. 3) and is thought to be reliable within 20 percent.

TABLE 1

	M	5μ flux (10^{-15} w/cm^2/μ)	N	10.2μ flux (10^{-16} w/cm^2/μ)	Q	22μ flux (10^{-18} w/cm^2/μ)
Lyr	0.00	2.2	0.00	1.2	0.00	5.7
Boo	-3.04	36.2	-3.30	25.1	-3.27	115.8
Aur	-1.91	12.8	-2.01	7.6	-1.94	34.0
Tau	-2.84	30.1	-3.11	21.0	-3.03	92.9
C Ma	-1.43	8.2	-1.41	4.4	-1.50	22.7

Based on our present knowledge, we can draw the following picture of the sky at 10 microns:

(a) Solar System - Mercury, Venus, Mars, Jupiter, Saturn, the Galilean satellites, Titan and, when they are close to the Earth, several asteroids such as Ceres, and Vesta and most comets are brighter than 1×10^{-16} w/cm^2/μ. Because of planetary motions and considerable temperature changes, these sources are all variable.

(b) Bright Stars: A 10,000°K star of zero visual magnitude produces a flux density at 10 microns of about 1×10^{-16} w/cm^2/μ; Vega (αLyra) is such a star. Cooler stars become brighter in the infrared relative to their visual brightness. There are several stars which are about 100 times brighter than Vega at 10 microns. There must be several hundred stars which equal or exceed the brightness of Vega at 10 microns, but the exact number is not yet known. Many of these stars are weakly variable at 10 microns.

(c) "Infrared" Stars: The Northern sky has been surveyed at 2.2 microns by the Cal Tech group. Of the 5,000 stars detected at 2.2 microns, about 20 have been found to radiate large amounts of infrared compared to ordinary cool stars. Most of the ~80 "infrared" stars which we have studied at 10 microns were found by observing members of certain special classes of stars which were suspected to have large infrared excesses. The infrared excess at 10 microns is produced by a cloud of dust surrounding the star which absorbs the hot radiation from the star and reradiates at a temperature between 50 to 1400°K. Many of these stars peak at 5 microns ($T \approx 600^{\circ}K$). The cloud of dust is produced by mass ejection from the star. Mass ejection is found in certain types of stars and can now be detected either by the resulting 10 micron excess radiation or by the presence of certain lines in their optical spectra. Using the optical spectra as a guide, we have found many infrared stars. So called T Tauri stars and many Fe emission stars are examples of this work. Recently we have found that Novae, which are stars which eject mass explosively rather than by continuous processes, become extremely bright infrared stars within a few days after outburst. There is evidence that infrared stars can be highly variable at 10 microns. Indeed, the number of such objects is constantly changing.

(d) "Infrared Nebulae": A number of extended infrared sources have been found in our galaxy. These bodies are cooler than 300°K, but extremely luminous, $>10^6$ times the power output of the sun. At the center of the galaxy, in the constellation Sagittarius, there is a complex of extended sources which is most clearly seen at 50 to 100 microns. In most cases, these sources are associated with so-called HII regions, places where extremely hot stars (10^5 to 10^{6}°K) have completely ionized the hydrogen gas. Throughout the galaxy, there are perhaps a few hundred such objects and most of them should be detectable at 10 microns at a flux level above 1×10^{-16} w/cm^2/μ. Examples are M17, M8, M42 and NGC 7027. Almost all of these galactic sources, including the "infrared" stars are concentrated into a few thousand square degrees of the sky near the plane of the Milky Way, with the greatest concentration in the direction of the galactic center. Away from the plane of the galaxy, these sources will be extremely rare. Thus, based on present knowledge, we might expect the maximum density of sources to occur in the plane of the Milky Way and that at a flux level $\geq 1 \times 10^{-16}$ w/cm^2/μ, the density could be as high as one source per 10 square degrees.

(e) "Infrared galaxies": Galaxies are randomly distributed on the celestial sphere and many galaxies are extra-ordinarily luminous in the infrared. Some galaxies are 100 to 1000 times more powerful in the infrared than at optical wavelengths. We have shown that the peak of the energy distribution is near 100 microns. 15 galaxies have been detected at 10 microns and two, M82 and NGC 1068, are as bright as 1×10^{-16} w/cm^2/μ. At lower flux levels, the number of extra-galactic sources will become extremely high. At 1×10^{-19} w/cm^2/μ, there should be about one source per square degree. M82 has been resolved at 10 microns into a source

about 15 x 30 arcseconds, however, most galaxies will appear as point sources and may vary with time scales as short as weeks.

The following bibliography may be helpful in pursuing this subject in greater detail:

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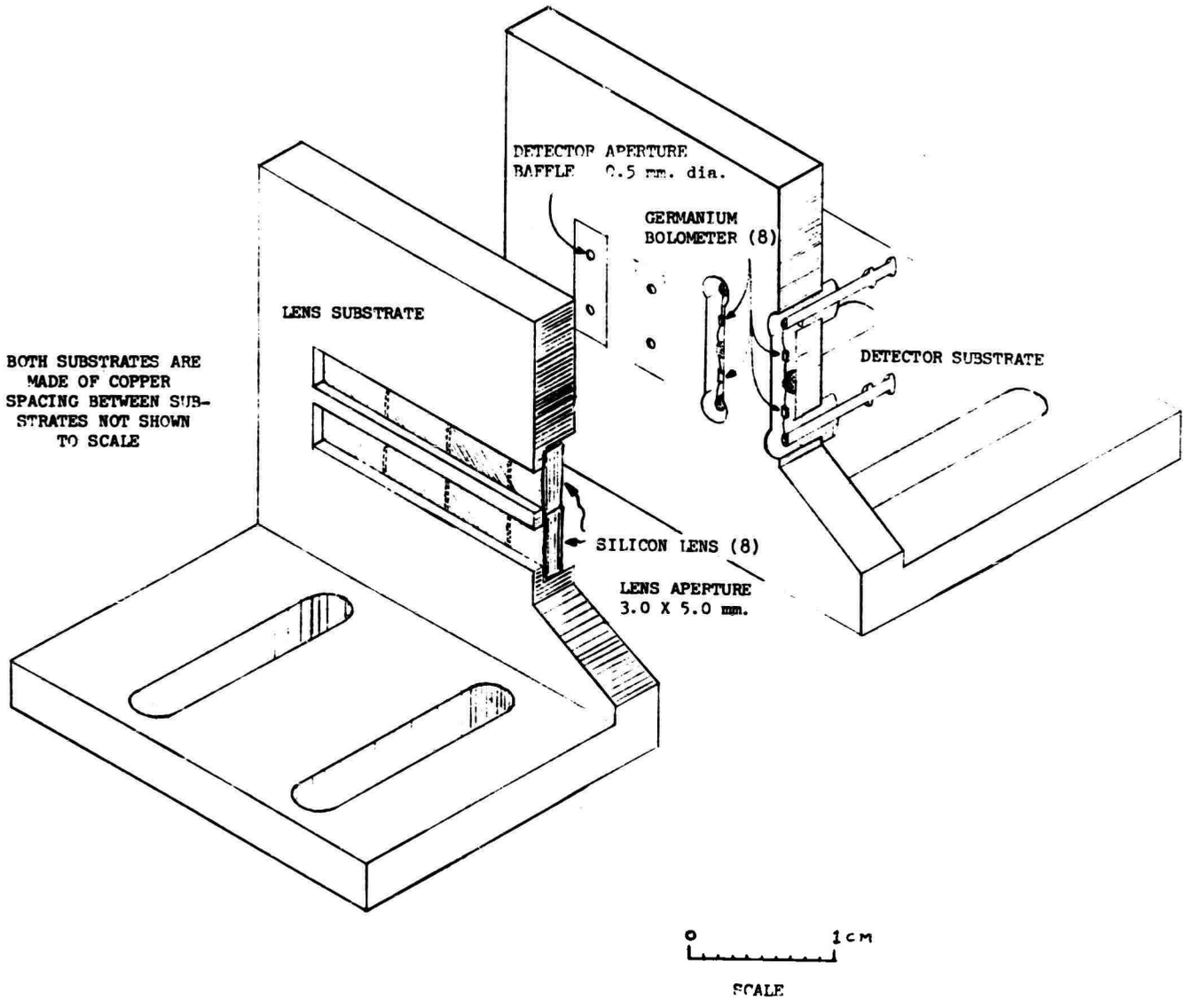
V. Technical Aspects of the Groundbased Infrared Sky Survey:

All infrared telescopes are ultimately limited by the fluctuating stream of photons from the background viewed by the detector. Here, the background is produced by thermal emission of the sky above the telescope and by emission within the telescope. As in all conventional groundbased telescopes, operating at ambient temperature, the latter source is predominant.

However, the sky emission fluctuates with time because of temperature, opacity and reflectivity imhomogenieties. This so-called "sky noise" phenomenon is the limiting source of noise at 10 microns for many days of the year. Even when the sky appears free of disturbances, these phenomena persist. However, there are many days when the "sky noise" at 10 microns is below the fundamental background noise level. At 5 and 22 microns, experience shows that the "sky noise" is much weaker than at 10 microns. Unfortunately, there has not been a systematic study of "sky noise", and we must talk in descriptive rather than quantitative terms. The "sky noise" problem arises again in connection with the modulator.

The detector is the all-important component in an infrared telescope. Here, we have relied exclusively on the helium cooled germanium bolometer (ref. 4). The reasons for this are the following: (a) When a cooled thermal detector, such as the bolometer, is background limited, the noise level is at least $\sqrt{2}$ times lower than for a photo-conductor operating under the same conditions. This is because the photo-conductor has generation and recombination noise, whereas in a thermal detector only the random arrival of photons produces noise, causing only half as many random events. In actual practice the difference is somewhat greater, presumably because the blackened bolometer has a higher quantum efficiency than copper or mercury doped germanium photoconductors. (b) The spectral power response of the bolometer is flat over the entire infrared band 2 to 25 microns, which is not the case for any other detector of comparable performance. Note that this is most important when the source temperature is above the background temperature and the spectral bandwidth is wide. (c) A practical consideration is the relative ease with which the bolometer can be designed and fabricated to the required specifications. It will be seen that these specifications include arrays consisting of four or more matched pairs of detectors.

In a background limited sky survey, the speed at which sky can be covered increases in proportion to the collecting area of the telescope and to the number of detectors. There are practical considerations which limit these two all important parameters. Here we have decided upon a 28-inch and a


DETECTOR APERTURE
BAFFLE 0.5 mm. dia.
GERMANIUM
BOLOMETER (8)
LENS SUBSTRATE
DETECTOR SUBSTRATE
BOTH SUBSTRATES ARE
MADE OF COPPER
SPACING BETWEEN SUB-
STRATES NOT SHOWN
TO SCALE
SILICON LENS (8)
LENS APERTURE
3.0 X 5.0 mm.
0
1 cm
SCALE

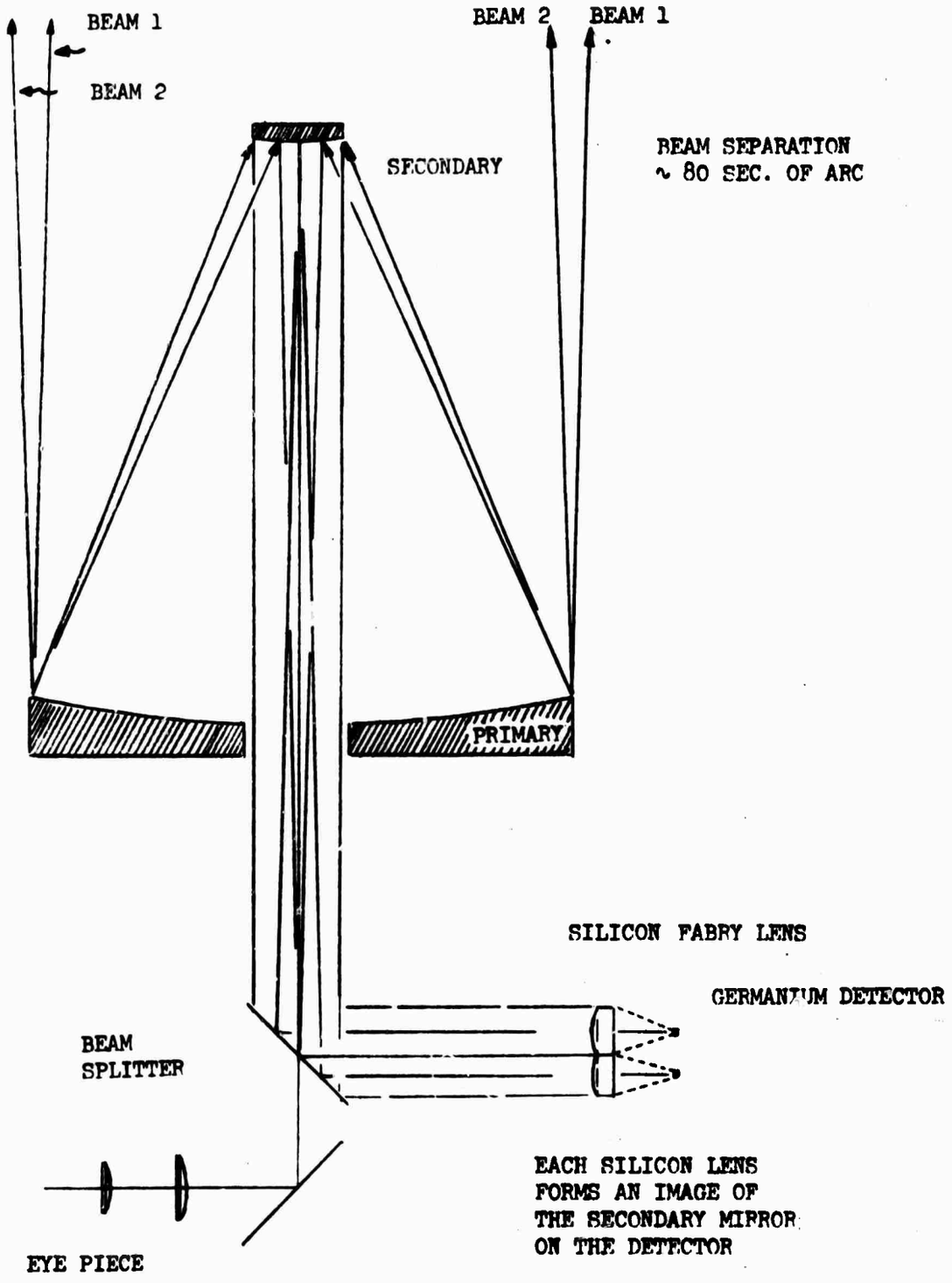
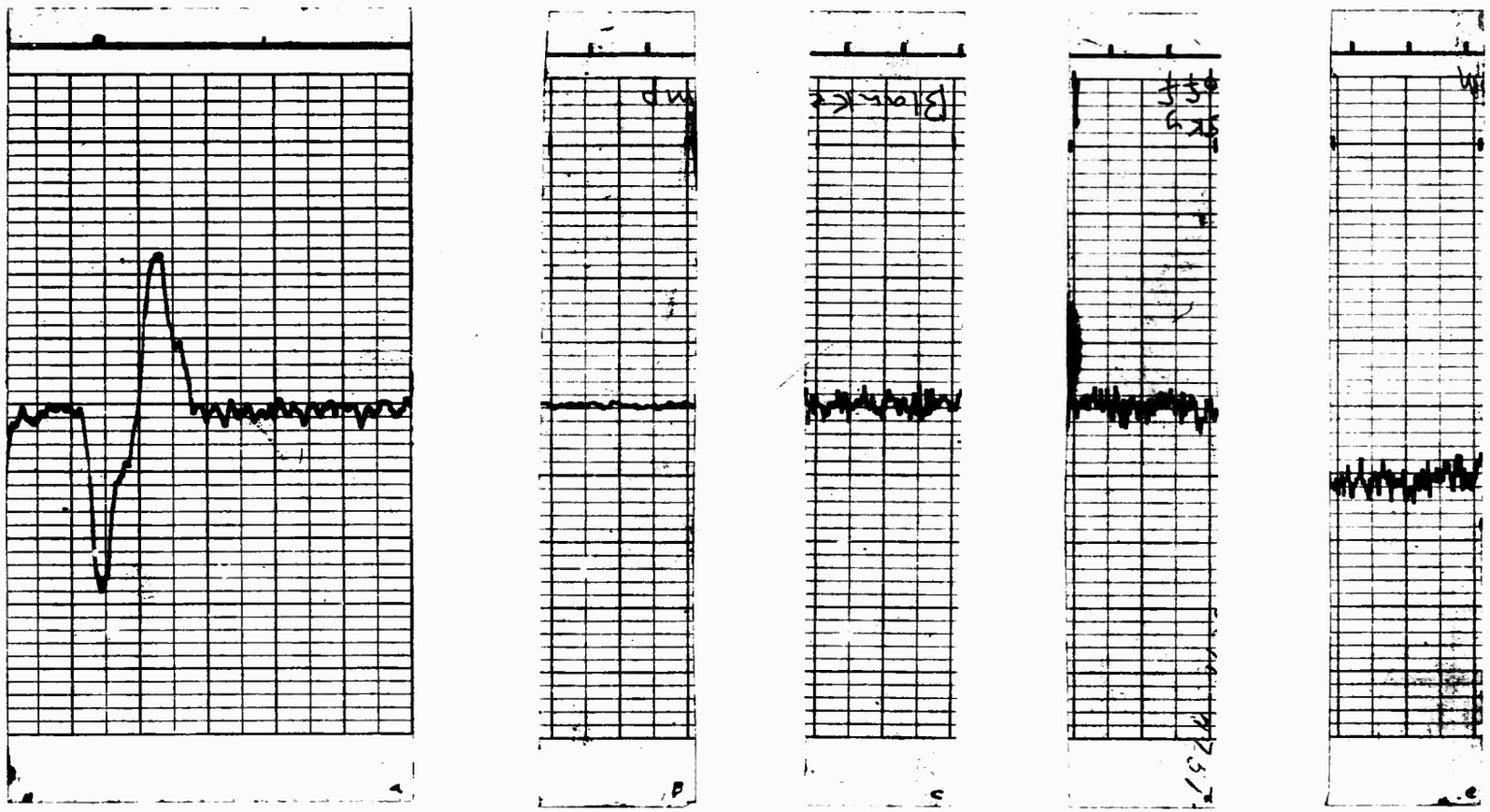


FIGURE 2. Diagramatic optical layout



(a) (b) (c) (d) (e)

FIGURE 3. (a) Scan of α Ori with single bolometer on 28" telescope. (b) Shorted pre-amplifier noise ($\sim 5 \times 10^{-9}$ v/Hz$^{\frac{1}{2}}$). (c) Bolometer noise blanked. (d) Sky with modulator off. (e) Sky with modulator on.

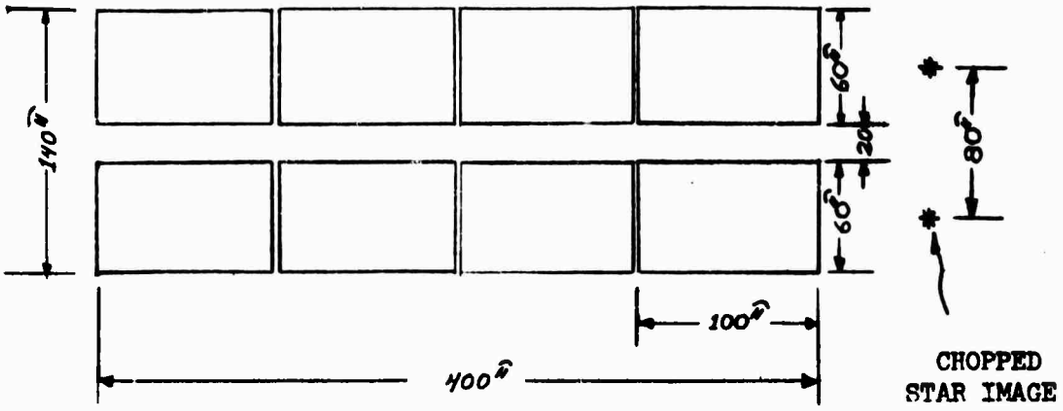


FIGURE 4. The 8 Si field lenses showing beam pattern as projected onto the sky by the 28" telescope (scale of the telescope is 18"/mm).

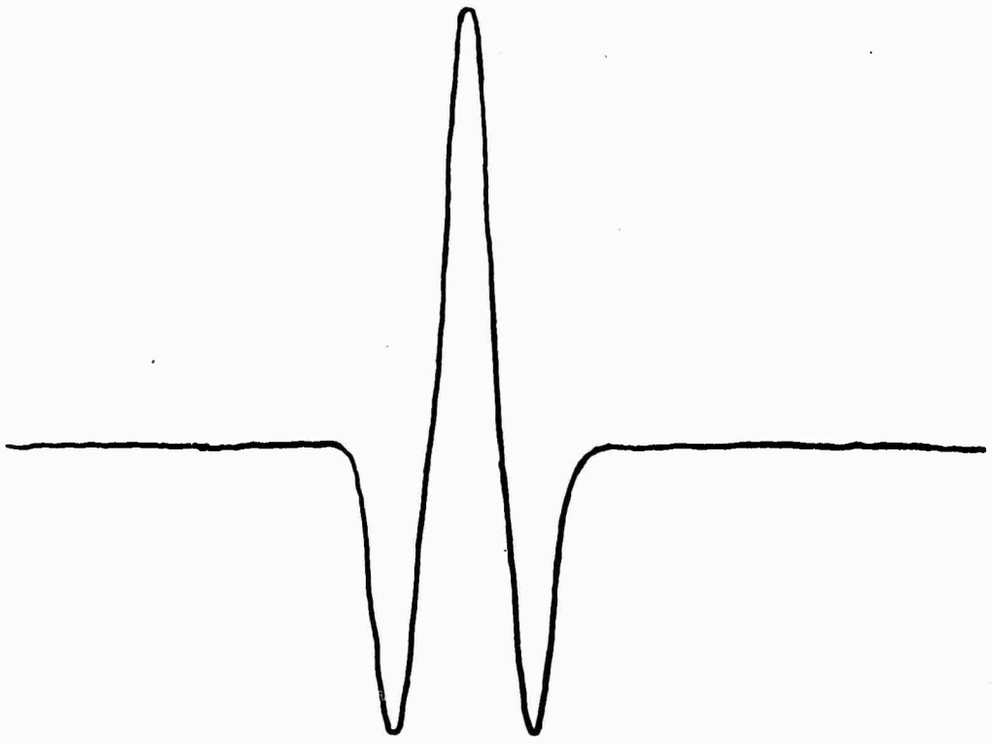
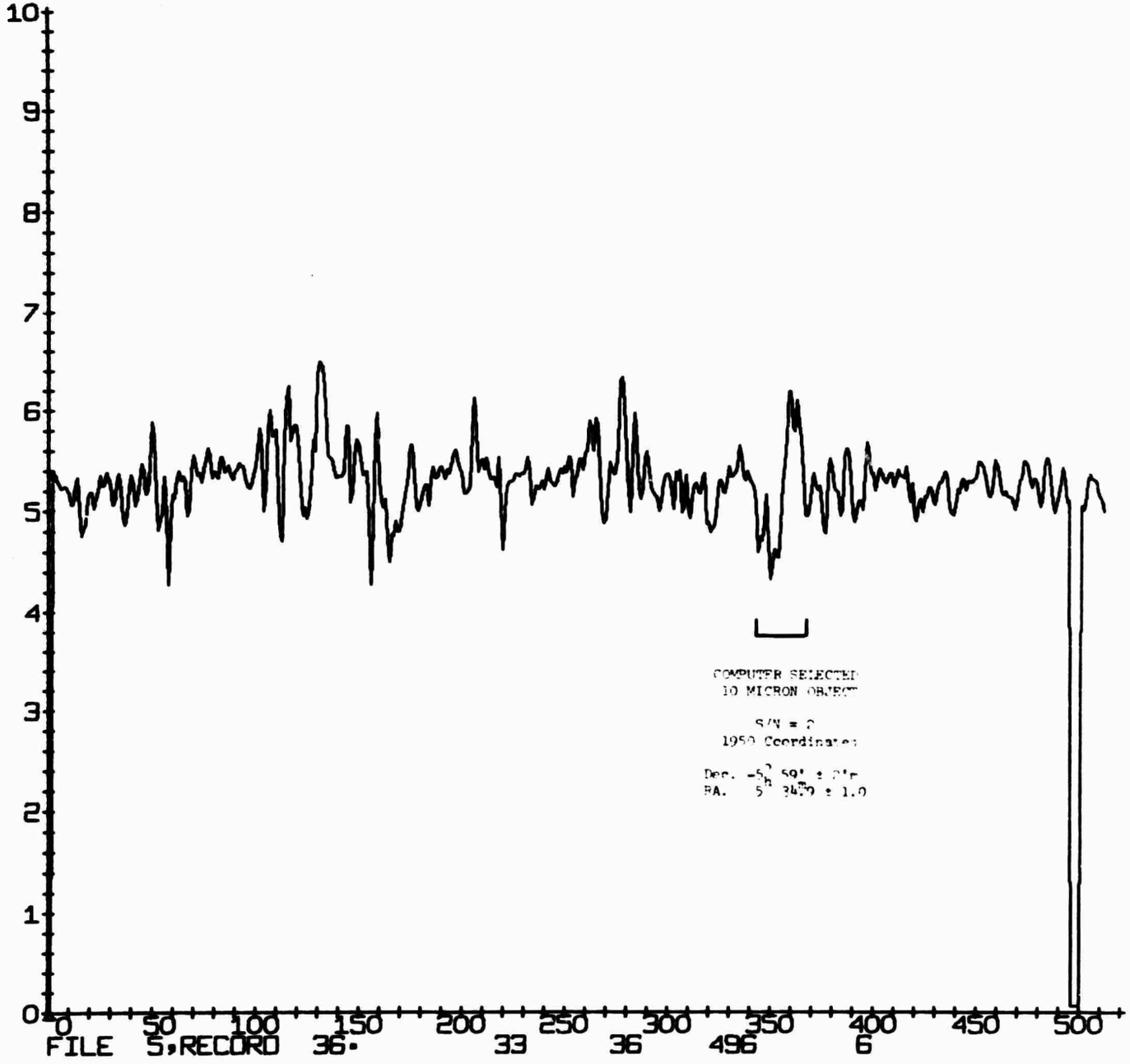
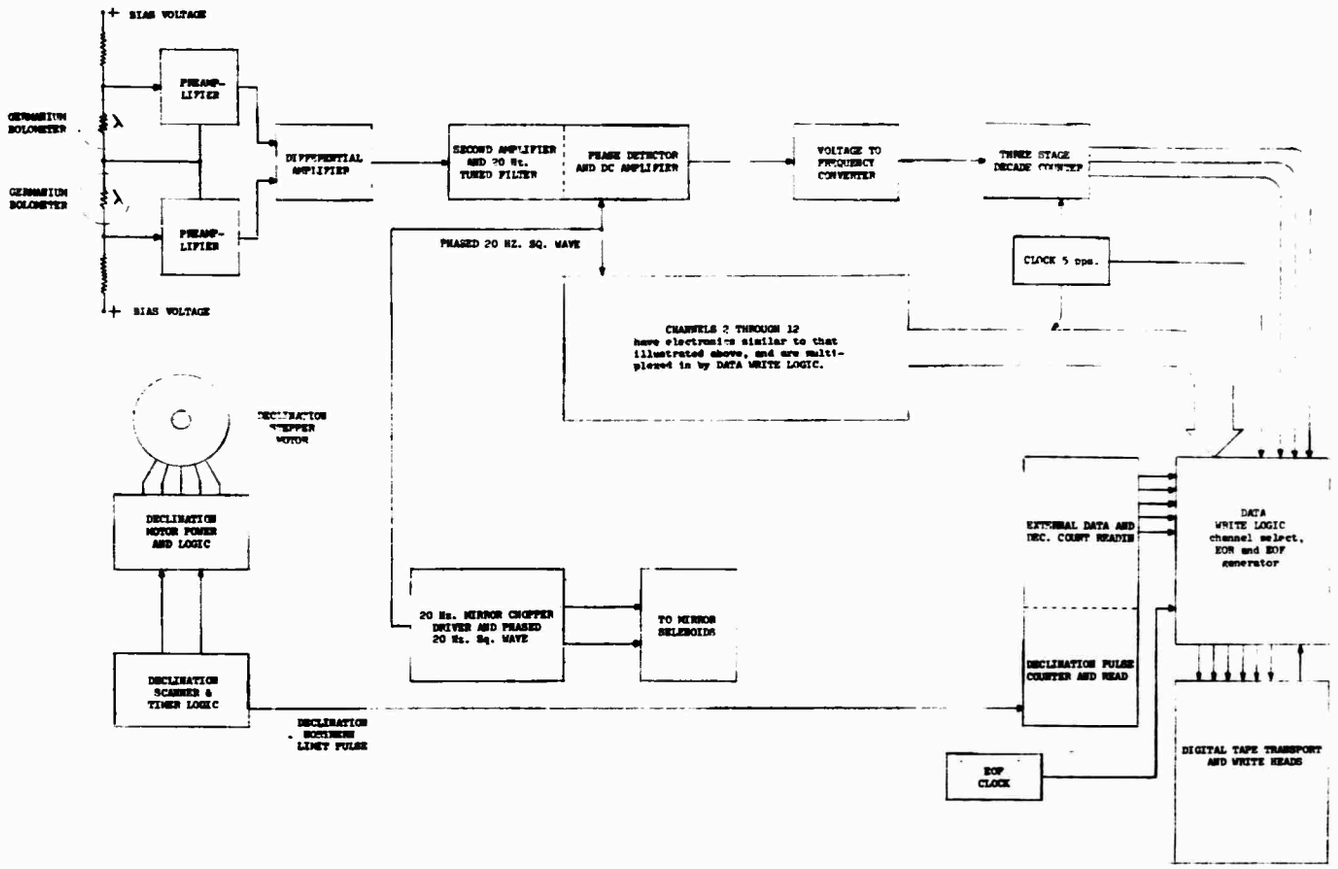


FIGURE 5. Signal produced by differentially connected pairs of detectors when the telescope is scanned in declination.



No. 00 RECORDING CHARTS GRAPHIC CONTROLS CORPORATION BUFFALO, NEW YORK


+ BIAS VOLTAGE
PREAMP-LIFIER
GERMANIUM BOLOMETER
GERMANIUM BOLOMETER
PREAMP-LIFIER
+ BIAS VOLTAGE
DIFFERENTIAL AMPLIFIER
SECOND AMPLIFIER AND 20 Hz. TUNED FILTER
PHASE DETECTOR AND DC AMPLIFIER
VOLTAGE TO FREQUENCY CONVERTER
THREE STAGE DECADE COUNTER
PHASED 20 HZ. SQ. WAVE
CLOCK 5 cps.
CHANNELS 2 THROUGH 12 have electronics similar to that illustrated above, and are multiplexed in by DATA WRITE LOGIC.
DECLINATION STEPPER MOTOR
DECLINATION MOTOR POWER AND LOGIC
DECLINATION SCANNER & TIMER LOGIC
20 Hz. MIRROR CHOPPER DRIVER AND PHASED 20 Hz. Sq. WAVE
TO MIRROR SOLENOIDS
DECLINATION ENCODER LIMIT PULSE
EXTERNAL DATA AND DEC. COUNT READIN
DECLINATION PULSE COUNTER AND READ
DATA WRITE LOGIC channel select, EOR and EOF generator
EOF CLOCK
DIGITAL TAPE TRANSPORT AND WRITE HEADS

21-inch telescope for most of the sky survey because of their availability. Limited use of a 60-inch telescope is feasible. An array of 8 detectors, each with an instantaneous field of view on the sky of 0.8 x 1.5 arcminutes, is used. Figure 1 shows a three dimensional view of the bolometer array and its associated Si field lenses. Figure 2 shows an optical diagram of the system. Note that the 3 x 5 mm. silicon field lens images the 0.5 x 0.5 mm. detector onto the objective of the telescope, thus minimizing the background. The design and construction of the cooled field optics is a critical step affecting both the efficiency and the background level.

In order to understand the geometry of the array and the reason why the detectors are connected as differential pairs, we must consider the modulation problem. We have developed a modulation system of the following type. The secondary mirror of the cassegrain telescope is mounted so that it can be rotated rapidly through a small arc between two fixed positions so that a star image in the focal plane is split into two equal images separated by a predetermined angular displacement. The mirror is driven back and forth 20 times per second with a travel time of only a few milliseconds. The actual displacement at the edge of the mirror is on the order of thousandths of an inch. In our system, the direction of modulation is in declination; therefore, the two images generated by the modulator pass across the detector as the telescope scans in declination. This produces a typical positive-negative deflection ("S" curve) after the signal is passed through a phase sensitive demodulator driven in the proper phase with respect to the secondary mirror. Figure 3 shows a typical output record produced by a single detector when the telescope is driven in declination. Note that even with this type of modulator, there is always a small offset voltage which must be cancelled by the d.c. amplifier.

By placing the detectors in two rows separated by the chopper throw as shown in Figure 4, and by connecting each pair of detectors to the input of a differential amplifier, the signal shown in Figure 5 is produced. This pattern provides a high degree of discrimination against spurious signals caused by non-celestial sources or by electrical interference. There is no degradation in signal/noise relative to a system with eight independent outputs and the signal recording and processing equipment is cut in half. This is a considerable saving in equipment and time.

A number of experiments were performed to determine the optimum spectral range to be used in the 10 micron window. It was found that a filter centered at 11.0 microns about three microns wide is the best choice. This corresponds to the "O" band used previously (ref. 5) and takes advantage of the high transparency and low emission of the atmosphere at these wavelengths.

Figure 6 is a block diagram of the entire multichannel system. After the phase-sensitive demodulator converts the 20 Hz. signal to a d.c. deflection, the d.c. amplifier and RC filter smooths the analogue signal before it passes on to the digitizer. The RC time constant is 0.20 seconds. The digitizer samples 5 times/sec. and generates a count between 000 and 999 which is

stored in BCD on magnetic tape. There are 18,000 three digit data points per hour of observing time for each of the four channels.

At present, a simple routine is used in data processing. First, the data points from one record are used to find the RMS noise. The points are examined to find peaks that are greater than two standard deviations. Once detected, an "S" curve is fitted to the data. If the fit is better than two standard deviations, the point in question is marked, and the data is stored for later plotting. Later, after the data has been plotted, these portions are checked for polarity and repetitiveness, and a judgment is made as to their probability of representing real sources. Figure 7 is a sample plot of the digitized data showing the possible source in Orion associated with the source reported by Walker and Price (ref. 1).

The positional accuracy of the survey is about ±1 arcminute in declination and ±0.5 minute of time in right ascension. The right ascension error will be reduced as soon as a new indicator system is added to the 28-inch telescope. There are two scan modes in use: (a) The telescope is set to a given declination and right ascension with the RA drive on, the dec. scan is started so that the telescope moves at a predetermined rate north and south, reversing after a precisely determined length of time, then the RA drive is switched off and the time noted; this mode covers a narrow strip of sky 12 to 20 hours in length per day. (b) The telescope is set up as in (a), but the RA drive is switched to $\sim$0.9 siderial rate allowing $\sim$10 times larger length of dec. scan. In mode (a), the telescope can be left unattended for as long as 20 hours, whereas in mode (b), the telescope must be reset every few hours at the end of each block.

The measured performance of the survey will now be discussed and compared to the theoretical performance. The results will be given for a single channel operating on the 28" telescope in mode (b). The following table lists the relevant data derived from operation of the system and from laboratory measurements. Note that the detector is background limited.

Observed flux level for p-to-p signal = RMS noise = 8.0×10^{-17} w/cm^2/μ
$\tau \equiv$ RC response time = 0.20 sec.
Scan length in dec. = 60 arcminutes
Scan length in RA = 120 arcminutes
Scan time = 1 hour
Scan area = 2 square degrees
Scan rate = 2 square degrees/hour

Instantaneous field of view = 0.8 arcminutes x 1.5 arcminutes
Measured background on telescope = 2.4×10^{-7} watt
Measured NEP at bolometer (20 Hz.) = 7×10^{-14} watt/Hz.$^{\frac{1}{2}}$
$\Delta F \equiv$ bandwidth = 2.5 Hz.
$\Delta\lambda \equiv$ Spectral bandwidth = 3.0 microns
λ eff. = 11.0 microns
Actual equivalent noisepower $\equiv$ NEP $\sqrt{\Delta F} = 1.1 \times 10^{-13}$ watt

28" telescope area = 3700 cm^2
Flux level for p-to-p signal = RMS noise (eff. = 100%) = 1.0×10^{-17} $w/cm^2/\mu$

It can be seen that the observed flux level is only 12.5% of the value calculated for a perfect (100% efficient) system. This system efficiency can be accounted for in the following way:

Si Field lens =	0.45
Interference filter =	0.85
Dewar window =	0.90
3 telescope mirrors =	$0.95^3 = 0.86$
Telescope obscuration =	0.94
Atmospheric attenuation =	0.95
Chopper =	0.85
Beam efficiency =	0.70
TOTAL	.15

In addition, we find that the signal reaches only 0.80 the true peak value when scanning, because the dwell time is slightly less than the full geometrical value based on a perfectly flat beam pattern. The quantity labeled beam efficiency refers to the part that diffraction at the field stop plays in preventing perfect illumination of the telescope.

It should be noted that the present level of efficiency is about a factor of 2 below what we can hope to achieve by improving components. This implies an improved S/N by a factor of 1.4 since background will increase.

We have studied the background emitted by the telescope and by the sky alone. We find that the telescope emits roughly as a blackbody with an emissivity of 0.5, whereas the sky is much colder having emissivities below 0.1 under the best conditions (precipitable H_2O <2mm.). Obviously, we must strive to reduce the emission from the telescope. A clear-cut factor of 2 in S/N seems possible.

In summary, we can state that sources at a flux level of 8×10^{-15} $w/cm^2/\mu$ (SN = 10) can now be detected on the 28" telescope when scanning at a rate of 2 sq. deg./hr. The new 8 detector array produces 1.4 times better sensitivy, and 4 times faster scan rate. When used on the 60" telescope, the limiting flux level should be 1×10^{-16} $w/cm^2/\mu$ at a rate of 4 sq. deg./hr. When all possible improvements are made, a factor of 3 increase in S/N seems likely.

VI. Present Status:

The first of two eight detector arrays is nearly complete and should be in full scale operation in October, 1970, covering 8 sq. deg./hr. on the 28". Experience has shown that about 1000 sq. deg./mo. is a likely rate for operation of the system (only about 25% of the days yield high quality data). At least half of this sky coverage will be concentrated in that portion of the sky where we expect the highest density of sources.

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The design, construction, operation and performance of a survey of the sky at infrared wavelengths is reported. A preliminary survey at 5 microns was conducted. This was followed by the more elaborate system using 8 detectors at 11 microns. Information concerning absolute calibration and performance is given.

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